MAGNETIC RANDOM ACCESS MEMORY DESIGNS WITH PATTERNED AND STABILIZED MAGNETIC SHIELDS

Tai Min, PoKang Wang

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to the use of magnetic tunnel junctions (MTJ) as storage elements (cells) in non-volatile magnetic memory cell arrays (MRAM). In particular it relates to MRAM arrays of shielded MTJ cells in which the cells have their uncompensated edge poles eliminated by magnetostatic coupling to magnetic shields and, in addition, are shielded from each other and from extraneous external magnetic fields by various forms and configurations of said shields.

2. Description of the Related Art

The magnetic tunnel junction (MTJ) basically comprises two electrodes, which are layers of ferromagnetic material, separated by a tunnel barrier layer, which is a thin layer of insulating material. The tunnel barrier layer must be sufficiently thin so that there is a probability for charge carriers (typically electrons) to cross the layer by means of quantum mechanical tunneling. The tunneling probability is spin dependent, depending on the orientation of the spin of the tunneling electrons relative to the

magnetization direction of the ferromagnetic layers. Thus, if these magnetization directions are varied, the tunneling current will also vary as a function of the relative directions for a given applied voltage. As a result of the behavior of an MTJ, sensing the change of tunneling current for a fixed potential can enable a determination of the relative magnetization directions of the two ferromagnetic layers that comprise it. Equivalently, the resistance of the MTJ can be measured, since different relative magnetization directions will produce different resistances.

The use of an MTJ as an information storage device requires that the magnetization of at least one of its ferromagnetic layers can be varied relative to the other and also that changes in the relative directions can be sensed by means of variations in the tunneling current or, equivalently, the junction resistance. In its simplest form as a two state memory storage device, the MTJ need only be capable of having its magnetizations put into parallel or antiparallel configurations (writing) and that these two configurations can be sensed by tunneling current variations or resistance variations (reading). In practice, the free ferromagnetic layer can be modeled as having a magnetization which is free to rotate but which energetically prefers to align in either direction along its easy axis (the direction of magnetic crystalline anisotropy). The magnetization of the fixed layer may be thought of as being permanently aligned in its easy axis direction. When the free layer is anti-aligned with the fixed layer, the junction will have its maximum resistance, when the free layer is aligned with the fixed layer, the minimum resistance is present. In typical MRAM circuitry, the MTJ devices are located at the intersection of current carrying lines called word lines and bit lines (or word lines and sense lines). When both lines are activated, the device is written upon, ie, its

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magnetization direction is changed. When only one line is activated, the resistance of the device can be sensed, so the device is effectively read. In this regard, Bronner et al. (U. S. Patent No. 6,242,770 B1) teaches a method for forming thin film conductors as word and bit lines so that the MTJ device is in close proximity to a lower line and a diode is located below that line.

In order for the MTJ MRAM device to be competitive with other forms of DRAM, it is necessary that the MTJ be made very small, typically of sub-micron dimension. Parkin et al. (U. S. Patent No. 6,166,948) notes that sub-micron dimensions are needed to be competitive with DRAM memories in the range of 10-100 Mbit capacities. Parkin also notes that such small sizes are associated with significant problems, particularly super-paramagnetism, which is the spontaneous thermal fluctuation of magnetization produced by in samples of ferromagnetic material too small to have sufficient magnetic anisotropy (a measure of the ability of a sample to maintain a given magnetization direction). Another size-related problem results from non-uniform and uncontrollable edge-fields produced by shape-anisotropy (a property of non-circular samples). These edge fields result in a large degree from randomly oriented magnetization vectors that form at the edges of the MTJ cells. These orientations have a tendency to curl back towards the magnetization vector of the body of the cell in an effort to minimize the magnetic energy of the cell. Such edge effects are also associated with uncompensated magnetic poles that form at the cell edges. As the cell size decreases, these edge fields become relatively more important than the magnetization of the body of the cell and have an adverse effect on the storage and reading of data. Although such shape-anisotropies, when of sufficient magnitude, reduce the disadvantageous effects of

super-paramagnetism, they have the negative effect of requiring high currents to change the magnetization direction of the MTJ for the purpose of storing data. To counteract these edge effects, Shi et al. (U. S. Patent No. 5,757,695) teaches the formation of an ellipsoidal MTJ cell wherein the magnetization vectors are aligned along the length (major axis) of the cell and which do not present variously oriented edge domains, high fields and poles at the ends of the element.

MTJ devices have been fabricated in several configurations, one type comprising a free ferromagnetic layer separated from a fixed (or pinned) layer. In such a configuration, the MTJ has data stored in it by causing the magnetization of its free layer to be either parallel or antiparallel to that of the pinned layer. The pinned layer may itself be a composite layer formed of two ferromagnetic layers held in an antiparallel magnetization configuration by some form of magnetic coupling so that it presents a zero or negligible net magnetic moment to the MTJ. Such an arrangement is advantageous in reducing edge effects due to anisotropies. Parkin, cited above, teaches an improved MTJ cell utilizing a free layer that comprises two ferromagnetic layers that are coupled by their dipolar fields in an antiparallel magnetization configuration to produce a small, but non-zero, magnetic moment. When written on by an external applied magnetic field, the two magnetic moments switch directions simultaneously so that the net magnetic moment of the free layer switches direction relative to the pinned layer. In addition, Gallagher et al. (U. S. Patent No. 5,650,958) teaches the formation of an MTJ device suitable for use in an MRAM array wherein the device comprises a free ferromagnetic layer and a pinned ferromagnetic layer which is pinned by interfacial exchange with an antiferromagnetic layer. Gallagher et al. (U. S. Patent No. 5,841,692) also teaches the formation of an MTJ

device having free and fixed layers wherein the fixed layer is formed as a sandwich of antiferromagnetically coupled ferromagnetic layers. Further, Shi et al. (U. S. Patent No. 5,959,880) teach the formation of a low aspect ratio MTJ device in which two layers of magnetoresistive material are separated by electrically insulating material.

It is undesirable for MTJ devices to have excessive magnetic coupling between adjacent magnetic layers of neighboring devices or even within the same device as this coupling must be overcome when writing on the device. As noted above, edge anisotropies are one source of undesirable coupling. Koch et al. (U. S. Patent No. 6,005,800) deal with the problem that results when writing to one specific cell also affects the magnetization directions of adjacent cells that are not being addressed. Koch teaches the formation of cells with two shapes, which are mirror images of each other. The cells are arranged in a checkerboard pattern, so that a cell of one shape is surrounded by cells of the other shape. Since neighboring cells thereby have their preferred magnetization vectors oriented differently, there is a reduced probability that writing to one cell type will affect the magnetization of the other type.

As has been discussed, many of the problems associated with the construction of MRAM arrays are related to the shapes of the cells. Cell shapes of present designs are typically single element rectangle, elliptical or lozenge. Chen et al. (U. S. Patent No. 5,917,749) provides a rectangular multi-layered MTJ cell comprising two rectangular magnetic layers magnetized in parallel directions along an easy axis corresponding to a direction of magnetic anisotropy and separated by a non-magnetic layer.

Any irregularities of these shapes, defects at their edges produced during their formation, or uncompensated poles of variable strength, will result in coercivity

fluctuations distributed throughout the array. It is the object of the present invention to control the problem of undesirable edge effects and non-uniform array coercivity more effectively than is done in the prior art by providing magnetic shields between arrangements of cells within an MRAM array. These shields serve several purposes, including providing pole compensation for edge poles of cell elements, shielding cells from the effects of external magnetic fields and shielding the magnetizations of individual cells from the effects of nearby cells. The use of shields to partially surround MTJ cells is not unknown in the prior art. Gill et al. (U. S. Patent No. 6,219,212 B1) provide an MTJ device for use as an MRAM cell or as a magnetic field sensor in a magnetic disk drive, in which magnetic material layers disposed above and below the MTJ device. The shields also act as current leads for the MTJ device. It is evident from the topology of the shielding layers that they are not intended to shield one such MTJ device from coplanar adjacent MTJ devices. Furthermore, it is also evident from the shield topology that they are not intended to cancel uncompensated poles formed at the edges of the magnetic free layer of the MTJ device.

SUMMARY OF THE INVENTION

A first object of this invention is to provide an MRAM array of MTJ cells wherein said devices are magnetically shielded from each other and from extraneous external magnetic fields.

A second object of this invention is to provide an MRAM array of shielded MTJ cells whose magnetization switching properties are insensitive to shape irregularities and edge defects.

A third object of this invention is to provide an MRAM array of shielded MTJ cells, in which array coercivity variations and resulting switching field variations due to shape irregularities and edge defects in the MTJ devices is eliminated or greatly reduced.

A fourth object of this invention is to provide an MRAM array of shielded MTJ cells in which problems of write selectivity, ie, writing onto unintended array locations, is eliminated or greatly reduced.

A fifth object of this invention is to provide an MRAM array of shielded MTJ cells which is less dependent on the shape of individual cell elements for its performance.

A sixth object of the present invention is to provide an MRAM array of shielded MTJ cells whose switching properties are uniform at all points of the array.

A seventh object of the present invention is to provide an MRAM array of shielded MTJ cells in which the threshold for switching is reduced.

An eighth object of the present invention is to provide an MRAM array of shielded MTJ cells meeting the above objects and in which the MTJ cells are densely deployed within the array.

These objects will be achieved by an MRAM array of shielded MTJ cells in which the shields compensate the free ferromagnetic layer of each MTJ cell at the edges of said cell. Additionally, said shields will also protect each MTJ cell in the MRAM array from the influence of extraneous external fields and from the undesirable influence

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of the fields produced by other MTJ cells in the array. The MTJ cell layers, insulating layers and shield layers are formed by methods of ion-beam deposition or chemical vapor deposition processes which are well known in the art. The shields are formed of ferromagnetic alloys and are patterned by the use of a photolithographic stencil and ion-beam milling subsequent to the formation and patterning of the cell array using the same stencil. The shields are thereby self aligned to the cell array and are shaped to conformally fit the individual MTJ cells. The shield will be electrically isolated from each memory cell by the formation of an insulating layer deposited prior to the shield formation. In accord with the objects of the invention, the uncompensated poles at the edges of the MTJ cells will be magnetostatically coupled to the shields so as to reduce the curling of magnetization and the formation of randomly oriented edge domains. The crystalline anisotropy of the shields can be set to be perpendicular to the crystalline anisotropy defining the easy axes of the MTJ cells. This will ensure that the shields and the cells are magnetized perpendicularly to each other. Such setting of crystalline anisotropy is produced by methods well known in the art, including the deposition of layers in appropriate magnetic fields. This mutual orthogonality of magnetization will enhance the magnetostatic coupling between the cells and the shields leading to more effective pole compensation. It is to be noted that the presence of uncompensated poles is highly disadvantageous because such poles constitute a high energy state of the cell. To minimize its energy, the cell will tend to produce magnetization curling by forming unstable, randomly oriented edge domains in the vicinity of the poles. These randomly oriented, unstable and uncontrollable domain states serve as nucleation sites for state switching (nucleation sites being positions at which there is the onset of a magnetization

change). Because the domains are randomly oriented, the state switching is non-uniform and leads to disadvantageous variations of switching thresholds and coercivity across the MRAM array. The shields provided by the present invention will prevent the formation of randomly oriented edge domains by serving as pole compensation mechanisms that eliminate the formation of such edge domains by providing an alternative mechanism for reducing the energy of the configuration. Further, the elimination of randomly oriented edge domains allows a uniformity of switching fields for the MRAM array. To insure that the magnetic shields themselves remain free of undesirable domain formations, the present invention also provides the additional formation of antiferromagnetic or permanent magnetic layers formed contiguously to the shields and maintaining them free of edge domains and stabilizing their magnetization.

The MRAM array is preferably formed of an array of MTJ cell configurations formed on a substrate in which cell-accessing conductive lines may already be present. Each cell preferably comprises a ferromagnetic free layer separated by an insulating tunneling junction layer from a fixed layer which is a magnetostatically coupled multilayer with zero magnetic moment comprising a first ferromagnetic layer having a first magnetization direction, a non-magnetic coupling layer, a second ferromagnetic layer having a second magnetization direction opposite to the first direction and an antiferromagnetic layer which pins the ferromagnetic layers of the fixed layer in their mutually antiparallel configuration. The configuration thus formed can then be patterned by a process of photolithography and ion milling well known in the art. Subsequent to the patterning, an insulating layer is formed surrounding the MTJ cells and, subsequent to that, the ferromagnetic magnetic shields are formed conformally surrounding the MTJ

cells, with their directions of magnetic anisotropy formed orthogonal to that of the MTJ cells. Finally, additional layers of permanent magnetic material can be formed adjacent to the shield layers to provide additional magnetic field stabilization of the shields. The cells in the array may be further covered by an insulating layer and additional conducting accessing lines may be formed above them.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig's. 1a-d are schematic illustrations of several different shield designs conformally patterned for elliptical MTJ cells.

Fig's 2a-c are schematic illustrations of shield designs stabilized by antiferromagnetic or permanent magnetic layers.

Fig's. 3a-e show a cross-sectional schematic illustration of the formation of a multi-layered MTJ cell surrounded by insulating layers and shield layers.

DESCRIPTION OF THE PREFERRED EMBODIMENT

The preferred embodiment of the present invention teaches a method of forming a shielded MRAM array of MTJ cells, said cells being substantially surrounded by and electrically insulated from a formation of ferromagnetic magnetic shields which conform to the shape of the MTJ cells and which may be stabilized by the formation of additional layers of antiferromagnetic and permanent magnetic materials. The magnetic shields compensate magnetic poles which would ordinarily form at the edges of the MTJ cells and shield the cells from undesired magnetic fields.

Referring first to Fig's 1a-1d, there is shown schematic overhead diagrams of an array of elliptical MTJ cells (20) surrounded by different shield (30) and gap (40) patterns. Any of these designs would meet the objects of the present invention and it is clear that other patterns may be equally appropriate if they satisfy the design criteria. The choice of MTJ cells which are substantially identical in their size and elliptical horizontal cross-section is for purposes of the example only and it is to be expected that substantially identical individual cells of a wide variety of isolated geometric horizontal cross-sectional shapes and sizes would be equally satisfactory as would cells composed of chains of discrete segments of a variety of shapes and sizes. Shields can be formed of the same ferromagnetic material as the ferromagnetic layers of the MTJ cells in the array, or they can be formed of different ferromagnetic materials. The material chosen, however, must be of sufficient magnetic softness (low coercivity) to allow magnetostatic coupling between the edges of the MTJ cells and the shields. The easy axis of the shield can be set by shape anisotropy or, preferentially, by crystalline anisotropy to be

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substantially perpendicular to the easy axis magnetization of the MTJ cells. This arrangement will enhance the magnetostatic coupling between the cells and the shields. It is also noted that the effectiveness of coupling between the shields and the MTJ cells requires that the shields at least partially conformally surround the cells. The conforming of the shield openings to the shape of the cell is provided in the present invention by a photolithographic and ion-milling process of the shields wherein the photolithographic stencil is formed around the photolithographic stencil already used to shape the cells. The process of forming such stencils and of ion-milling using said stencils as ion-milling masks is well known in the art and is not described herein.

Referring next to Fig's 2a-c, there is shown schematic overhead diagrams of shielded MRAM arrays in which additional contiguous layers of stabilizing magnetic material (50) have been added in variously patterned configurations around the ferromagnetic shield material (30) which is shown partially surrounding four MTJ cells (20). An exposed gap region of insulation is also shown (40). The stabilizing material can be antiferromagnetic material, such as PtMn, NiMn, IrMn, OsMn, PdPtMn, NiO, CoO or CoNiO which exchange couples to the ferromagnetic shield portion or permanent magnetic material, such as Co, CoCr, CoCrPt, CoPt, CoCrB, CoPtB, CoP or CoNiFe, which directly couples to the ferromagnetic portion. Either material will accomplish the desired object of eliminating magnetic domains within the ferromagnetic shields (30) and thereby stabilizing the coupling between the ferromagnetic shields and the memory cells (20). Fig. 2a shows a strip (50) of either antiferromagnetic or permanent magnetic material formed along the bottom edge of the ferromagnetic shield (30). Fig. 2b shows

three such strips (50) formed horizontally through the ferromagnetic shield (30). Fig. 2c shows three vertical strips (50) passing through the ferromagnetic strips (30).

Referring to Fig. 3a, there is shown a cross-sectional view of a multilayered MTJ structure designed to efficiently achieve the objects of the present invention subsequent to it being patterned to form an array. A brief summary of the MTJ structure formation is discussed below.

The MTJ structure is formed on a substrate (5) within which conducting lines (8) may already have been formed to contact the underside of the MTJ structure. The MTJ structure is formed of a ferromagnetic free layer (10), which may be a multilayer, separated by an insulating tunneling layer (30) from a magnetically pinned layer (20). It is understood that the crystalline anisotropy directions of the free and pinned ferromagnetic layers may be set in preferred directions during the formation of those layers so that the easy axis of magnetization is along that direction. In this preferred embodiment, the crystalline anisotropy direction will be the same in all ferromagnetic layers although the final directions of the magnetization may be parallel or antiparallel to that direction.

The pinned layer (20) is a multilayer, comprising a first ferromagnetic layer (22) and a second ferromagnetic layer (26) separated by a coupling layer (24) formed of non-magnetic coupling materials such as Rh, Ru, Cr or Cu formed to a thickness between approximately 5 and 50 angstroms. The magnetizations of the first and second ferromagnetic layers are exchange coupled in antiparallel directions across the coupling layer of properly chosen thickness and the magnetization of the second ferromagnetic layer is pinned by an antiferromagnetic layer (28) such as a layer of PtMn, NiMn, OsMn,

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IrMn, NiO or CoNiO, positioned adjacent to the second ferromagnetic layer and formed to a thickness between approximately 30 and 300 angstroms. The material composition and thicknesses of the first and second ferromagnetic layers are chosen so that their magnetizations are essentially equal in magnitude. Thus, when they are fixed in opposite directions, the net magnetic moment of the pinned layer is substantially zero. In the preferred embodiments herein, the materials of these pinned layers as well as the free layers are ferromagnetic materials such as NiFe, CoFe, CoNiFe, CoFeB, CoZrB, CoHfB, FeN and they are formed to a thickness between approximately 5 and 500 angstroms. It may be advantageous to also form the ferromagnetic free layer as a multilayer comprising two ferromagnetic layers coupled with their magnetizations in an antiparallel configuration across a non-magnetic layer of either Rh, Ru, Cr, or Cu, in a manner similar to the formation of the pinned layer, with the caveat that the net magnetic moment should not be zero, since the free layer must be switched by the word line field..

Referring next to Fig. 3b, there is shown the structure of Fig. 3a now formed into a cell having a top (90) and sides (92). The cell will be formed with a certain horizontal cross-sectional shape in accord with the objects of the present invention using photolithographic and ion-milling methods in which a photolithographic stencil shaped in accord with the desired shape of the MTJ cell is formed on the structure and the stencil then is used as a photolithographic mask for producing the required geometric shape by ion-milling. Since such processes are well know to those skilled in the art, they are not described further herein. It has also been noted above that the photolithographic stencil for the cell shape is allowed to remain for purposes of self aligning a subsequent

photolithographic stencil to be used in forming the magnetic shields. This process is also well known in the art and is not described herein.

The cell shape can be any of a wide variety of isolated geometrical forms such as ellipses, lozenges, notched geometric forms, forms having the narrowest dimension at their middle, or chains which are multiple discrete segments of such forms. To be consistent with the illustrations of Fig's 1 and 2, the horizontal cross-sectional shape will be considered as being elliptical. Fig. 3b shows only one elliptical segment, (100) and, since it is seen in profile, the fact that it is elliptical is not evident. It is further understood that in forming an array of such cells, the multilayered structure of Fig. 3a would be shaped by a single photolithographic and ion-milling process into an array of cells substantially identical to the single cell indicated in this figure.

Referring next to Fig. 3c, there is shown, the cell of Fig. 3b, (100), whereon an insulating layer (120) has been formed conformally (contacting contiguously) over the sides of the cell (92) and overlaying at least a portion of the substrate surrounding the cell (95). If an array of cells is being formed, the insulating layer would be formed conformally covering the sides of all cells in the array and the exposed substrate surfaces surrounding them. The insulating layer would preferably be a layer of dielectric material such as Al_2O_3, HaO_2, ZrO_2 or SiO_2, formed to a thickness between approximately 100 and 1000 angstroms. Depending upon the size of the array and the shape of its elements, the insulation deposition may be done in a single step or as a series of steps.

Referring next to Fig. 3d, there is shown the cell (100) of Fig. 3c subsequent to the formation of a magnetic shield layer (200) over the insulation layer (120), said shield layer conformally surrounding the cell by uniformly contacting and abutting the

insulation layer on the sides of the cell (92). The formation of the shields can be most advantageously accomplished by a self-aligned process in which the photolithographic stencil used for forming the cell array is not removed after cell array formation, but remains and is also used to form the insulation layer and the shield. The stencil is removed subsequent to the entire process. Such processes are well known in the art and are not illustrated herein.

The shields may then be formed of the same ferromagnetic material as is used to form the ferromagnetic layers of the cell or of other soft (low coercivity) ferromagnetic material. A shield of CoFe formed to a thickness of between approximately 10 and 1000 angstroms would be preferred, but materials such as NiFe, CoFe, CoNiFe, CoFeB, CoZrB, CoHfB, FeN, which can also be used to form the ferromagnetic layers of the MTJ cell, are also appropriate when formed to thicknesses between approximately 10 and 1000 angstroms. In the process of forming the shields, the crystalline anisotropy of the shield can be controlled and set in various directions relative to the crystalline anisotropy of the free ferromagnetic layers of the MTJ cells by forming the shield in the presence of an approximately 30-60 Oe field in the desired anisotropy direction. A direction of shield anisotropy that is orthogonal to that of the MTJ cells and a subsequent magnetization of the shields which is also orthogonal to that of the MTJ cells is preferable and is found to maximize and stabilize magnetostatic coupling between the cells and the shields. The shield formation process also allows control of the coercivity of the shield material and a coercivity in the range between 0 and 200 Oe is preferable.

Referring next to Fig. 3e, there is shown the formation of an additional insulating layer (210) over the magnetic shield and the formation of an additional conducting layer (300) over the insulated shield and contacting the upper surface of the MTJ cell. The overlaying conducting layer (300) will be patterned so that together with the conducting word lines (8) already formed (typically, separately from the cell array) within the substrate, reading and writing on the cell will be allowed and, in particular, reading and writing on selected cells of the array will be allowed. It is noted that methods of forming word lines within the substrate on which the MTJ cell array is formed are well known in the prior art and are not described herein.

It is understood that to achieve the objects of the invention the formation of the shields can include the patterning of regions within which stabilizing layers of antiferromagnetic or permanent magnetic materials can be formed in accord with the illustrations in Fig's 2a-c. The formation of such additional layers requires an additional patterning process for the shields and the use of the same patterning stencil to produce a self-aligned formation of the permanent magnetic layers adjacent to the shields. The magnetization of the permanent magnetic layer is then set perpendicularly to the magnetization of the MTJ cell. An antiferromagnetic layer, if used, is deposited on top of the shields to obtain the required exchange coupling.

As is understood by a person skilled in the art, the preferred embodiment of the present invention is illustrative of the present invention rather than being limiting of the present invention. Revisions and modifications may be made to methods, processes, materials, structures, and dimensions through which is formed an MRAM array of

shielded MTJ cells, while still providing an MRAM array of shielded MTJ cells formed in accord with the present invention as defined by the appended claims.

What is claimed is: